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STRUCTURAL CHARACTERISTICS OF FATIGUE FRACTURES OF SPECIMENS AND PARTS MADE OF HEAT-RESISTANT ALLOYS

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It is shown that the characteristic features of fatigue failure of heat-resistant materials are the simultaneous appearance of many fracture foci, development of failure along several surfaces in a crystal grain and also the appearance of many primary cracks in the first stages of failure. Fatugue failure of heat-resistant alloys differs from the non-fatigue type mainly by the presence of micro slip surfaces which form a folded grain fracture surface relief.

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In plant laboratory practice it is often necessary to determine the nature of a fracture (fatigue, brittle, etc.) according to the condition of its surface.

Analysis of fatigue fractures of specimens and parts made of nickel-chromium-base heat-resistant alloys (deformed EI437 and EI617 types, as well as the cast) is complicated since these

fractures do not have the features which are observed in typical fatigue fractures of construction steels.

Fatigue fractures of heat-resistant materials have certain general features which are characteristic of those of specimens and parts made of aluminum and magnesium alloys. Hence, their structural characteristics are explained not only by the specific operating conditions but also by the structure of the material itself.

In order to clarify these basic characteristics, a number of fractures of specimens, operational parts (blades and disks of gas turbines) and blades, which had been tested on a special machine (Figure 1) on which it was possible to bend them along the plane of least rigidity, were subjected to visual examination and fracture analysis /See Note/.

/Note: Ya. B. Fridman, T. A. Gordeyeva and A. M. Zaytsev, Stroyeniye i Analiz Izlomov Metallov (The Structure and Analysis of Fractures of Metals), Mashgiz /Gosudarstvennoye Nauchno-Tekhnicheskoye Izdatel'stvo Mashinostroitel'noy Literatury -- State Scientific and Technical Publishing House of Literature on Machine Building/, 1960./

In order to prevent failure at the place of attachment, two notches were made across the blades at a distance of 20 mm from the top of the blade roots and to within 15 mm of the opposite edge. The blades were stressed statically with a suspended weight (with the blade root clamped in a horizontal plane) and

also by variable loading with the aid of an eccentric mechanism. Calibration of the testing machine, which operates on the principle of constant deformation, was performed by direct loading. The working section of the blade was heated to the required temperature by a burner through the controlling nozzle of which a gasoline-air mixture was supplied. Temperature was measured with an optical pyrometer. A supply of compressed air was provided through another nozzle to prevent overheating of the bearings and electric motor of the machine.

Turbine blades made of the deformed EI437B alloy and the cast alloy were tested with the aid of the machine described above (see the table).

The main differences in the structure of fatigue fractures of heat-resistant materials and those of construction steels are as follow. In fractures of heat-resistant materials the focus and seat of failure are less clearly defined. This is connected with the fact that not one, but many crack foci is the characteristic of the fatigue failure which appears under the simultaneous action of variable stresses and high temperatures. In operational fractures of parts of gas turbines which frequently experience the effect of long-duration static stresses along with the variable stresses in operating conditions, the presence of a multitude of foci is even more pronounced.

The focus of fracture is usually in the form of a facet which has a smoother surface than the other facets in the zone of fatigue

BLADE TESTING CONDITIONS

Blade material	Testing temperature, °C	Amplitude value of stresses, kg/mm^2	Number of cycles to failure	Remarks
EI437B	20	—	1	Testing was conducted by single-stage stressing to complete failure.
EI437B	700	—	1	
Cast alloy	20	—	1	
" "	700	—	1	
" "	20	±57	8,000	
" "	20	±85; ±21	254,000	Testing was conducted under conditions of periodically changing stress amplitude values.
" "	20	±90; ±35	1,410,000	
" "	600-700	±47	2,540,000	Blades were tested under twelve heat cycles.
" "	600-700	±68	1,288,000	
" "	800-20	±42	108,000	Blades were tested under four heat cycles.
" "	800-20	±50	32,500	
" "	800	±42.5	65,000	Blades were tested up to crack formation.
" "	800-20	±41; ±57	82,000	Stresses and temperature were changed periodically.
EI437B	800	±52; ±73	32,500	Stresses were changed periodically; blades were tested up to crack formation.

crack formation (Figure 2). In contrast to construction steels, the portion of the surface which is the focus of fracture of heat-resistant materials is not always perpendicular to the direction of the highest tensile stresses. Frequently these areas are very small and differ insignificantly in structure as compared with the remaining portion of the fatigue zone and are therefore difficultly defined. In such cases the intitial zone of failure is determined according to the orientation of the ridges which appear as the result of confluence of the surfaces of fractures which began from various foci arranged in sequence. In addition, the "folded" relief of microsurfaces, which will be discussed below, also has an orientation which is generally directed toward the initial zone of failure. As a fracture propagates deeper into the material, the height of the ridges decreases. However, as the result of the appearance of initial cracks-tears at considerable distances from each other, in a number of cases the ridges do not merge into a common surface of failure up to the zone of final fracture. In particular, this pertains to the ridges which are located at a distance from the initial basic seat of failure. Due to the presence of the folds and ridges which form with the confluence of the neighboring cracks-tears, the initial zone of fracture is not the smoothest. As confluence of the ridges progresses, the fracture surface becomes smoother and sometimes acquires a ground appearance (Figure 3).

Obviously the characteristic features of fatigue failure of

of heat-resistant materials are thus the simultaneous or practically simulteneous appearance of many foci, the development of failure along several slip surfaces in a crystal and also the appearance of many primary cracks-tears in the initial stages of failure. The lines resembling hyperbolas which were observed (under a magnification of 200) at the seat of fatigue failure of a specimen made of the cast alloy testify to the appearance of many local foci and to the subsequent confluence of the initial cracks into a single surface of fracture (Figure 4).

On fractures of heat-resistant materials, as should be the case, no clearly defined fatigue lines passing through an entire fracture section of a specimen or part are observed. In a careful examination of the surface of fractured grains (at a magnification on the order of 20-40), it is possible to detect wave-shaped lines which begin and end within the limits of a grain. However, the presence of such lines is not always the case.

Despite the absence of typical fatigue lines, the course of development of failure is most frequently illustrated by the presence of various-colored oxide films arranged in the form of ring-shaped bands on the fracture surfaces. For the given alloy, at low temperatures or high stresses and relatively rapid development of failure, the color bands on a fracture can be very weakly defined or absent entirely.

At the same time, fatigue fractures of heat-resistant materials

are observed which have sufficiently clearly defined fatigue lines which pass through an entire fracture section (Figure 5). As is usually the rule, typical fatigue lines are present in the case of failure of the given alloy at relatively low temperatures and considerable vibration stresses. When fatigue lines of any form are present, they are most clearly defined in the zone adjoining the final fracture zone and usually have the form of continuous ring lines which pass over the entire fracture section.

The most clearly defined feature which distinguishes fatigue failure of heat-resistant alloys from the non-fatigue type is the presence of micro slip-surfaces which form a folded relief on the surface of a fractured grain (Figure 6).

The surface of the fatigue zone of fracture consists of small surfaces, practically all of which are oriented differently in space. These surfaces are obviously the surface of failure within the limits of a single grain and, in certain cases, several adjoining grains with identical orientation. On the small micro-surfaces it is possible to detect a smooth portion and a portion with a folded relief which extends from the smooth zone. The folded condition is of a unidirectional character within the limits of a single area; it is either fan-shaped (arrow 1 in Figure 6) or of practically a parallel character (arrow 2 in Figure 6). It can be assumed that the folded character of the

elementary surfaces is the result of failure along several adjoining slip planes and the confluence of these surfaces into a single fracture surface /See Note/.

/Note: S. V. Serensen and G. P. Meshchaninova, "Certain Characteristics of Fatigue Failure of Alloys at Elevated Temperatures," Ustalost' Metallov, Sb. (Fatigue of Metals, A Collection of Articles), Publishing House of the Academy of Sciences USSR, 1960./

The fan-shaped arrangement of the folds can be the result of a preliminary turn of the portions of a crystal about one or another crystallographic axis.

The portions of accelerated development which are manifested on typical fatigue fractures as zones of "brittle slippage" are not apparent on fractures of heat-resistant materials.

The zone of final fracture in fractures of heat-resistant materials can be of different structure; it can be either granular or columnar, which corresponds to failure along grain boundaries (Figure 7) or through the grains proper. Preliminary observations did not make it possible to establish a regular connection between the test conditions (magnitude of the stresses, temperature) and the structure of the final fracture zone. Inasmuch as the structure of the final fracture zone can be one of the indications which would make it possible to establish the operating conditions and the reason for failure of a part while in operation, it is

expedient to conduct a special investigation to clarify the effect of the value of the stresses and temperature on the structural characteristics of the final fracture zone.

The structural features of fatigue fractures of heat-resistant materials which have been enumerated above are observed in tests of cylindrical specimens, in tests of blades on the machine described and also in operational failures, for example, those of blades and disks of gas turbines.

It should be noted that in actual operating conditions the blades of a turbine function under more complicated stress conditions than those employed in this work. As a result, the structure of operational fractures differ somewhat from those obtained in our tests mainly by the arrangement of the individual zones in a fracture. With respect to the effect of a constant tensile stress and high temperature, failure of a blade vane begins with the formation of cracks which pass along grain boundaries and are characteristic for long-duration static stressing. In a number of cases, the portion of static failure is very small and extends only within the limits of one to three grains; in addition to the cracks which have developed on the surface of a blade vane, a number of finer cracks and tears are noted which also proceed along grain boundaries. Further failure occurs as fatigue failure with the formation of a fracture having the structural characteristics enumerated above.

Only in cases of relatively low operating temperatures

(approximately 500-550°C for alloy EI437B and 700-800°C for the cast alloy) and considerable vibration stresses does failure begin and proceed as fatigue failure, occurring basically in a grain proper.

Failure of the root portion of blades and the inter-anchor portions of turbine disks is most frequently completely of a fatigue nature. These fractures differ somewhat in structure from the portions of fatigue fracture of a blade vane. In the given case, signs of "granulation" failure along individual grains are less sharply defined: the fatigue lines frequently have the form of continuous lines which pass through the entire fracture section and the folded relief of the individual micro-portions has a more general directivity over the entire fracture. As is usually the rule, seats of fracture occur more frequently on the blade root than on the smooth surface of the blade profile. In addition to the two principles which cause the formation of many seats of failure (the effects of high temperature and static stresses) there is also the effect of a macroscopic concentrator which is in the form of the longitudinal grooves of the anchor attachments.

FIGURE APPENDIX

Figure 1. General view of a machine for fatigue testing of blades: 1 - blade being tested; 2 - nozzle for heating the blade; 3 - nozzle with the cooling mixture.

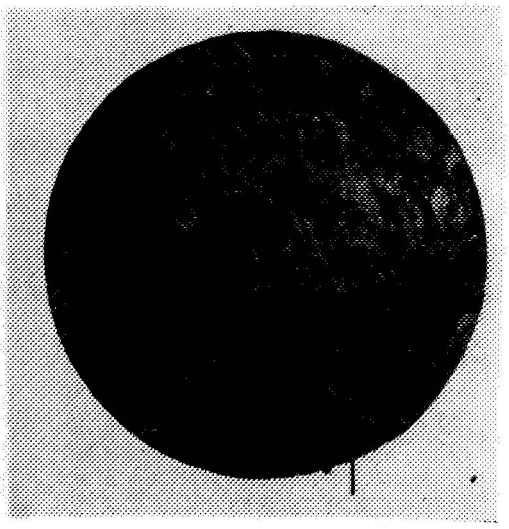

Figure 2. Seat of fatigue fracture (indicated by an arrow) of a blade made of alloy EI437B (testing temperature, 550° C).

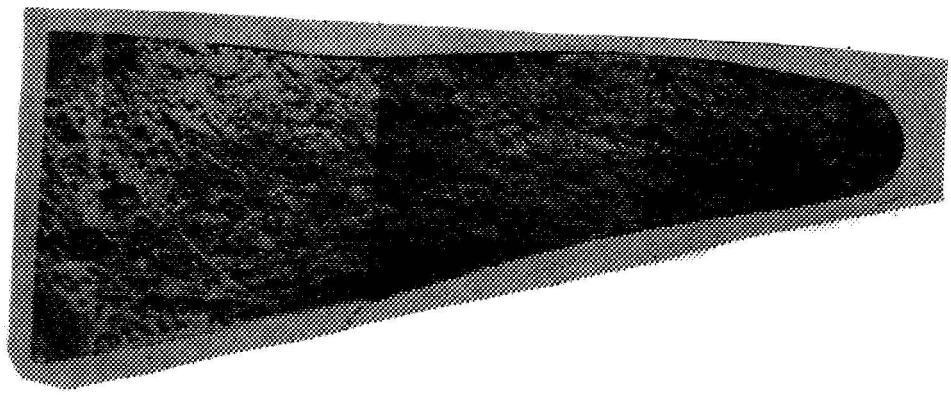

Figure 3. Portion of a fatigue fracture of a blade made of alloy EI437B (temperature, ~550° C); sequence photography, X4.

Figure 4. Seat of fatigue fracture of a specimen made of the cast alloy (testing under variable symmetrical bending at a temperature of 900° C), X200.

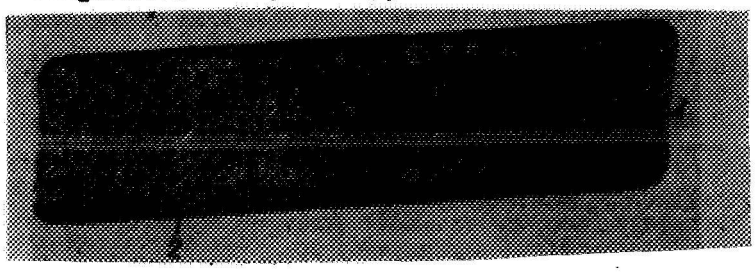

Figure 5. Fatigue fracture of a blade root (alloy EI437B, temperature of ~ 500° C), X1.4:
1 - fatigue zone; 2 - final fracture zone.

Figure 6. Surface of a micro area on a fatigue fracture (alloy EI437B, temperature of ~700° C), X200.

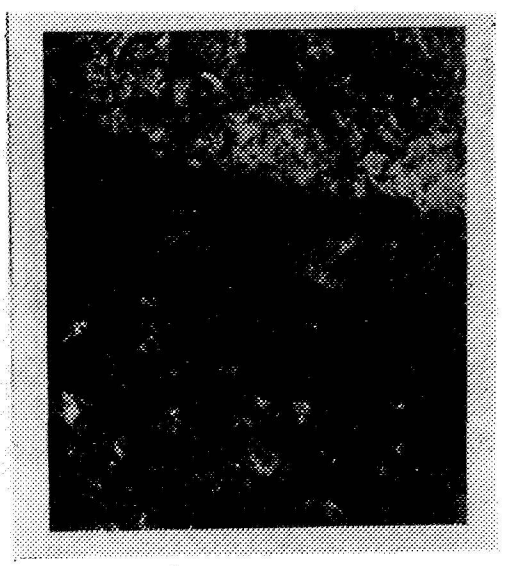

Figure 7. Structure of the final fracture zone of a fatigue fracture (alloy EI437B), X15.

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